# NOVEL THERMAL CONTROL CONCEPTS USING MICRO HEAT PIPES - SPACECRAFT THERMAL CONTROL

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# REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188



1. REPORT DATE (DD-MM-YYYY)
30-05-2001

2. REPORT TYPE
Workshop Presentations

3. DATES COVERED (FROM - TO)
30-05-2001 to 01-06-2001

4. TITLE AND SUBTITLE
Novel Thermal Control Concepts Using Micro Heat Pipes - Spacecraft Thermal Control
Unclassified

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Peterson, G. P. ;

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME AND ADDRESS
Department of Mechanical Engineering,
Aeronautical Engineering and Mechanics
Rensselaer Polytechnic Institute
Troy, NY12180

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME AND ADDRESS
Office of Naval Research International Field Office
Office of Naval Research
Washington, DCxxxxx

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
APUBLIC RELEASE
,

13. SUPPLEMENTARY NOTES
See Also ADM001348, Thermal Materials Workshop 2001, held in Cambridge, UK on May 30-June 1, 2001. Additional papers can be downloaded from: http://www-mech.eng.cam.ac.uk/onr/

14. ABSTRACT
? MICRO HEAT PIPE CONCEPTS ? Wire Bonded Micro Heat Pipe ? Polymer Micro Heat Pipe ? EXPERIMENT FACILITY

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:

| a. REPORT | b. ABSTRACT | c. THIS PAGE |
|---|---|---|
| Unclassified | Unclassified | Unclassified |

17. LIMITATION OF ABSTRACT
Public Release

18. NUMBER OF PAGES
36

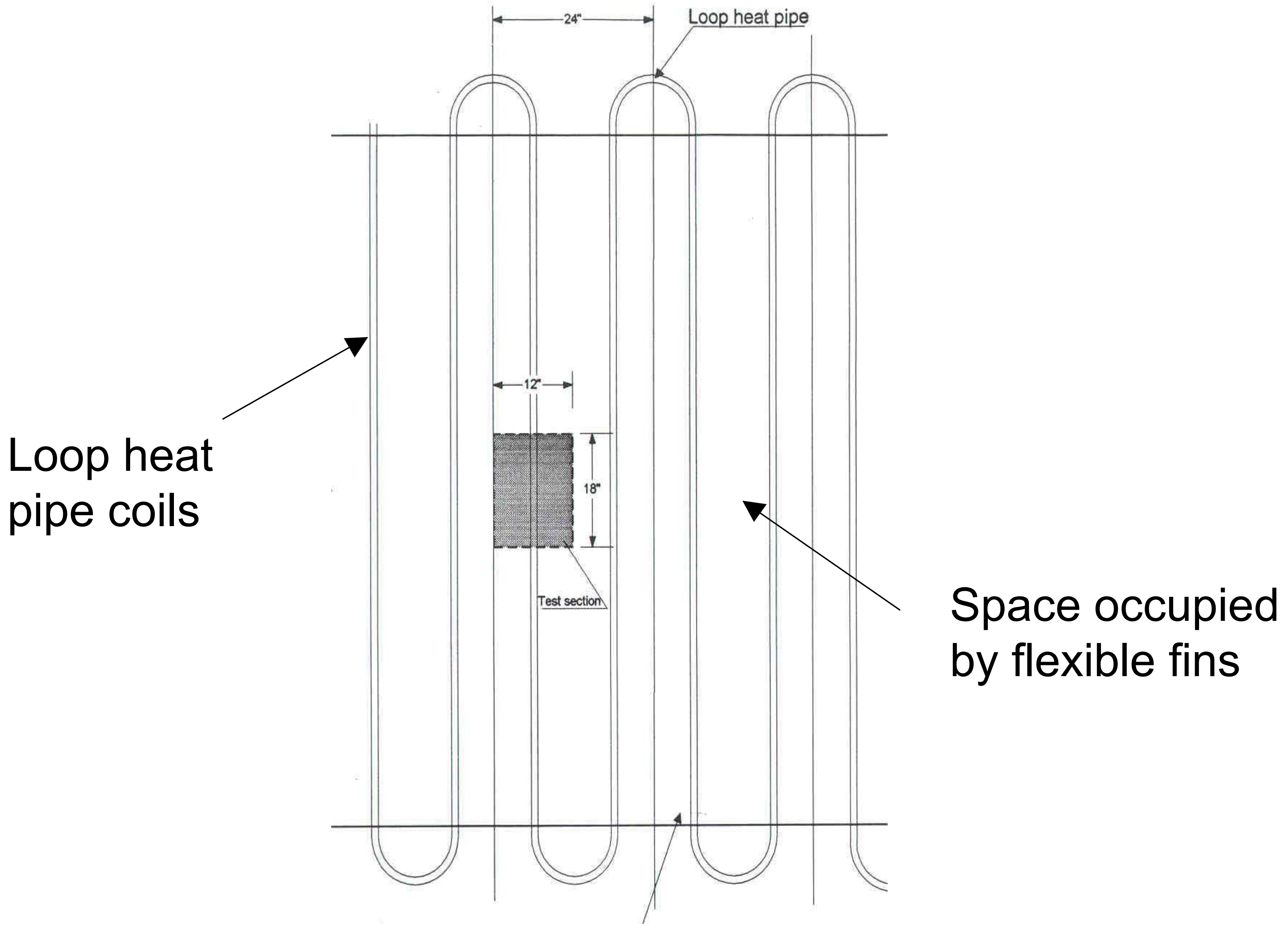
19. NAME OF RESPONSIBLE PERSON
Fenster, Lynn
lfenster@dtic.mil

19b. TELEPHONE NUMBER
International Area Code
Area Code Telephone Number
703767-9007
DSN
427-9007

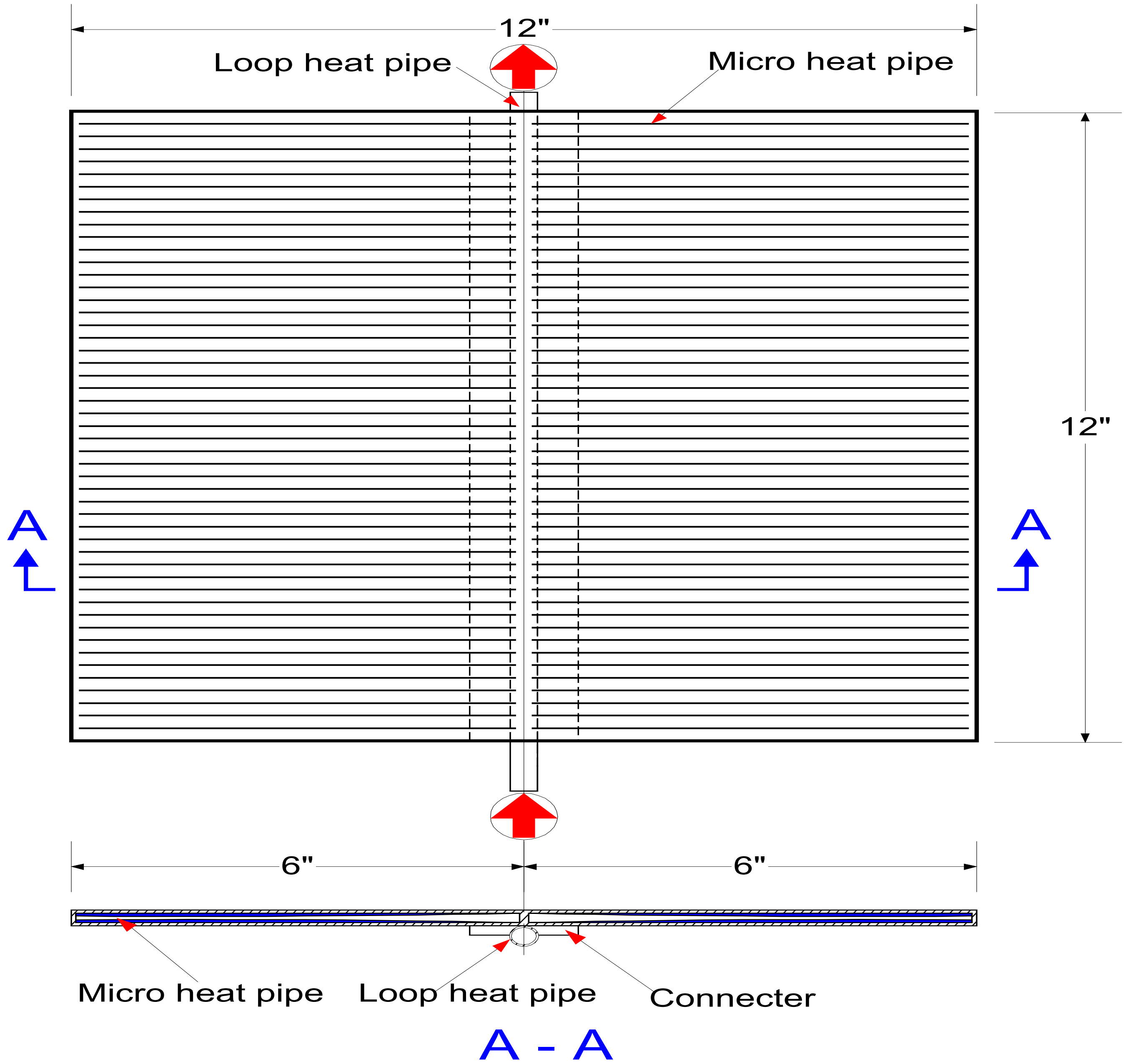
Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39.18

# Introduction

- **BACKGROUND**
- **MICRO HEAT PIPE CONCEPTS**
  - **Wire Bonded Micro Heat Pipe**
  - **Polymer Micro Heat Pipe**
- **EXPERIMENT FACILITY**
- **RESULTS & DISCUSSION**
- **CONCLUSIONS**



24"
Loop heat pipe
12"
18"
Test section
Loop heat pipe coils
Space occupied by flexible fins



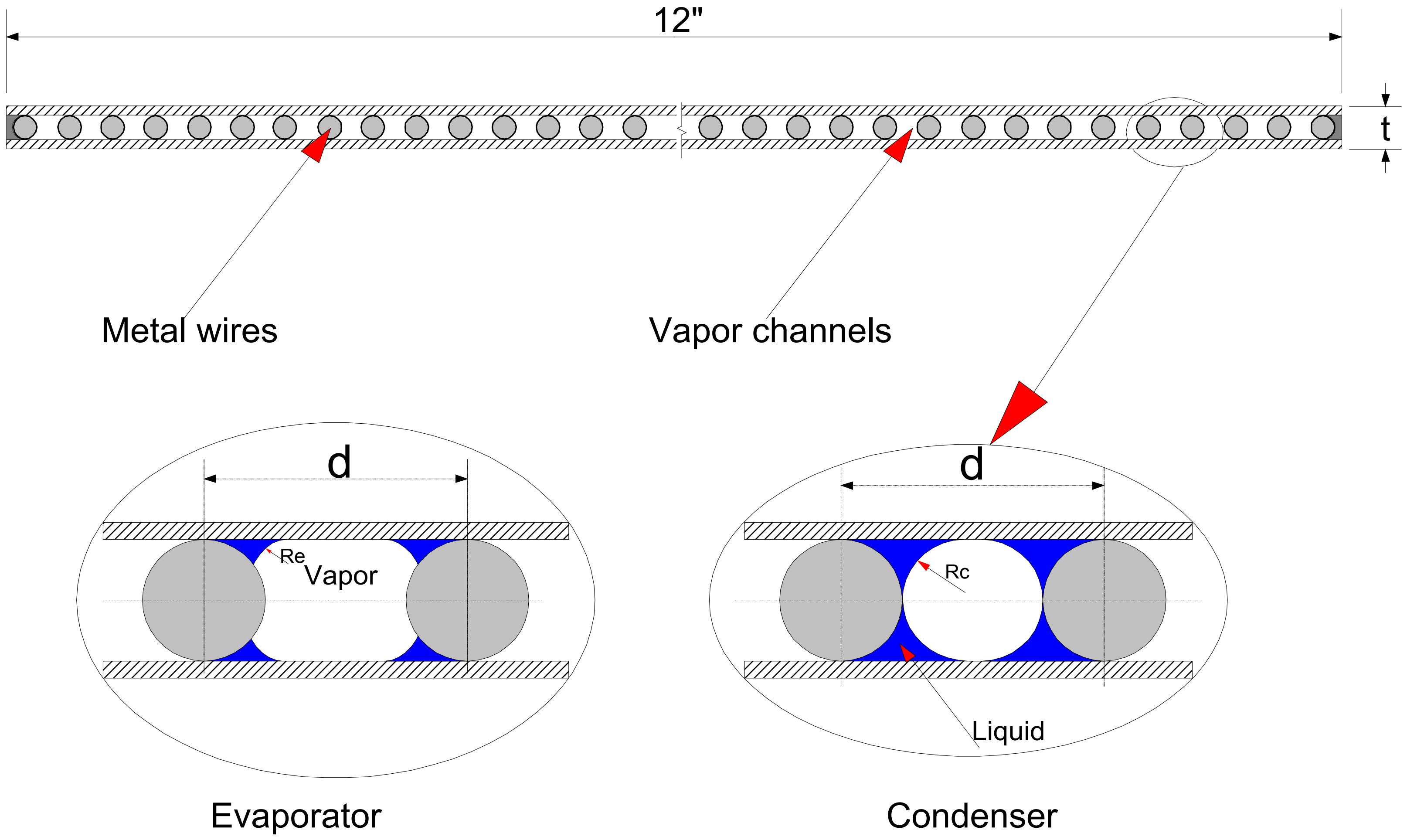
12"
Loop heat pipe
Micro heat pipe
12"
A
A
6"
6"
Micro heat pipe
Loop heat pipe
Connecter
A - A

# Initial Concepts

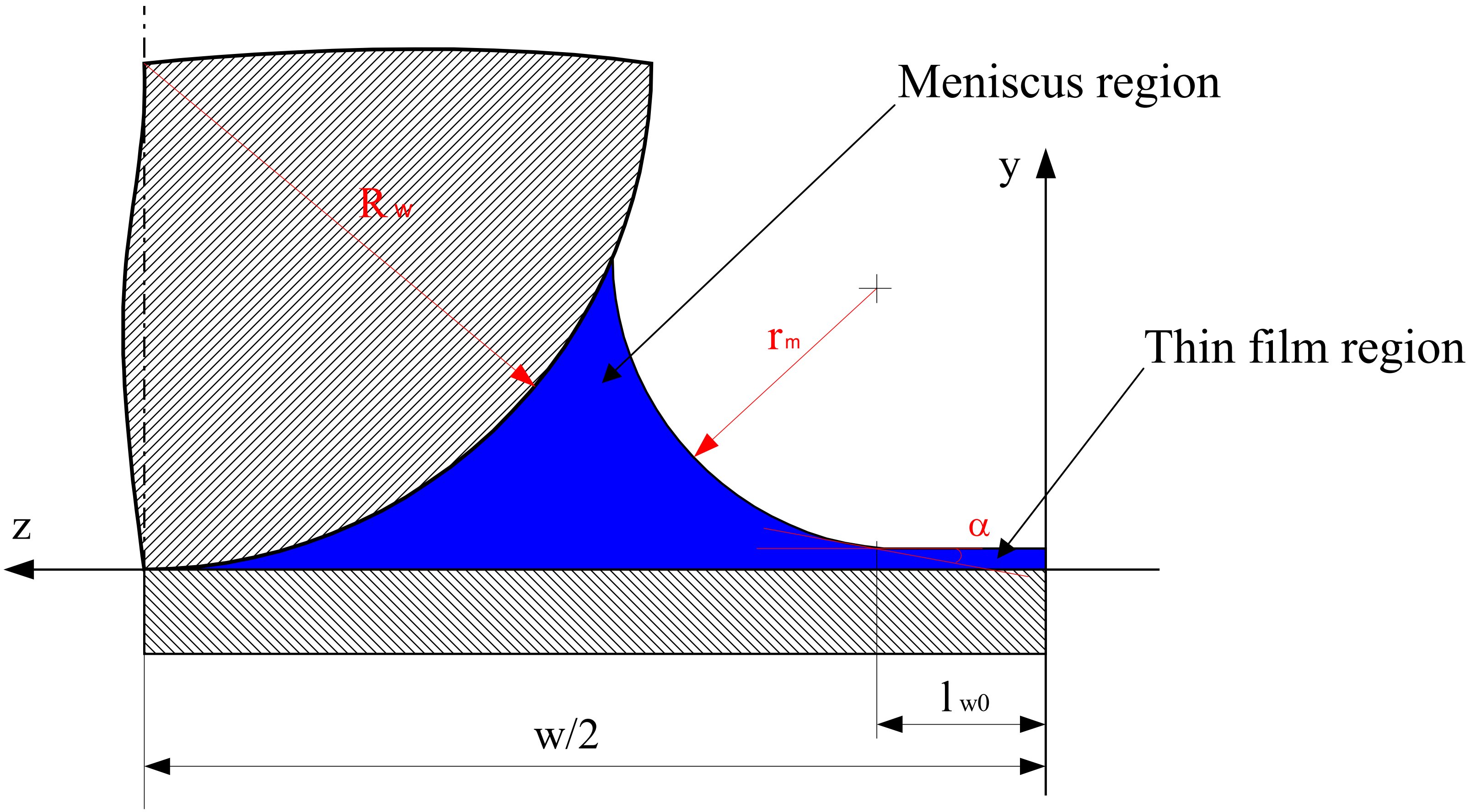
**From an initial group of six concepts, the following were selected for further study**

- **Wire bonded heat pipe array**
- **Flexible Polymer Heat Pipe**

# Flexible Wire Bonded Micro Heat Pipe



# Liquid Distribution



# Geometric Parameters

$$\beta_1 + \beta_2 + \alpha = \frac{\pi}{2} \qquad R_w \sin^2 \beta_1 = r_m \cos \beta_1 \sin \beta_2$$

$$\beta_1 = a\tan\left[\frac{1}{2R_w}\left(-r_m \sin\alpha + \left((r_m \sin a)^2 + 4R_w r_m \cos\alpha\right)^{\frac{1}{2}}\right)\right]$$

$$A_{c,l} = 2R_w r_m \sin\beta_1 \sin\beta_2 - R_w{}^2(\beta_1 - \sin\beta_1 \cos\beta_2) - r_m{}^2(\beta_2 - \sin\beta_2 \cos\beta_2)$$

$$A_{c,v} = R_w(2w - \pi R_w) - 4A_{c,l} \qquad l_{ac} = 2R_w \beta_1$$

$$l_{ab} = \left[(r_m \sin\alpha)^2 + 4R_w r_m \cos\alpha\right]^{\frac{1}{2}} - r_m \sin\alpha \qquad l_{cb} = 2r_m \beta_2$$

# Fluid Flow Model

Continuity Equations

$$\frac{d(u_l A_{c,l})}{dx} - v_{l,i} p_i = 0 \qquad \frac{d(u_v A_{c,v})}{dx} - v_{v,i} p_i = 0$$

Momentum Equations

$$-\rho_l(2A_{c,l}u_l\frac{du_l}{dx} + u_l{}^2\frac{dA_{c,l}}{dx}) - A_{c,l}\frac{dP_l}{dx} + p_{l,i}\tau_{l,i} + p_{l,w}\tau_{l,w} - g\rho_l A_{c,l}\sin\theta = 0$$

$$\rho_v(2A_{c,v}u_v\frac{du_v}{dx} + u_v{}^2\frac{dA_{c,v}}{dx}) + A_{c,v}\frac{dP_v}{dx} + p_{v,i}\tau_{v,i} + p_{v,w}\tau_{v,w} + g\rho_v A_{c,v}\sin\theta = 0$$

Energy Equations

$$v_{l,i} = \frac{q''w}{2\rho_l p_{l,i} h'_{fg}} \qquad v_{v,i} = \frac{2wq''}{\rho_v p_{v,i} h'_{fg}}$$

# Fluid Flow Model

The condenser exposed in radiation:

$$q_c'' = h_{c,o}(T_v - T_{\sin k})(1 + \frac{h_{c,o}}{\overline{h}_c})^{-1}$$

$$h_{c,o} = \varepsilon\sigma_0(T_{w,o} + T_{\sin k})(T_{w,o}{}^2 + T_{\sin k}{}^2)$$

$$v_{v,i} = \frac{2wh_{c,o}(T_v - T_{\sin k})\left(1 + \frac{h_{c,o}}{\overline{h}_c}\right)^{-1}}{\rho_v p_{v,i} h_{fg}}$$

In the adiabatic section:

$$q_a'' = 0$$

In the evaporator section:

$$q_e'' = cons\tan t$$

$$v_{l,i} = \frac{wh_{c,o}(T_v - T_{\sin k})\left(1 + \frac{h_{c,o}}{\overline{h}_c}\right)^{-1}}{2\rho_l p_{l,i} h_{fg}}$$

# Heat Transfer in the Evaporator

Heat transfer in evaporating film:

$\Delta Q_1 = 0$

$$\Delta Q_{2+3} = \int_0^{z'_2} \frac{T_{w,i} - T_v}{\dfrac{1}{h_{ph}} + \dfrac{\delta(z')}{k_l}} dz'$$

$$\Delta Q_{2+3} = \int_0^{z'_2} \frac{T_{w,i} - T_v}{\dfrac{1}{3.2\rho_v h_{fg}}\left(\dfrac{T_v}{R_g}\right)^{0.5} + \dfrac{\left(\delta_0 - r_m + \left(r_m{}^2 + z'^2\right)^{0.5}\right)}{k_l}} dz'$$

$$\Delta Q_4 = \int_{z'_2}^{2r_m \sin\beta_1 \sin\beta_2} \frac{(T_{w,i} - T_v)}{\left(1/h_{ph} + z'^2/2r_m k_l\right)} dz'$$

$$\bar{h}_{ph} = 3.2\rho_v h_{fg}\sqrt{\frac{R_g}{T_v}}$$

$$= 1.41(T_{w,i} - T_v)(h_{pc} k_l r_m)^{\frac{1}{2}}\left[\frac{\pi}{2} - a\tan\left(\frac{h_{ph}\delta_2}{k_l}\right)^{\frac{1}{2}}\right]$$

$$h_{e,men} = \frac{\Delta Q_{2+3} + \Delta Q_4}{\left(T_{w,i} - T_v\right) l_{ab}}$$

$$\bar{h}_e = \left\{\left[\frac{2l_{ab}}{w} h_{e,men}\right]^{-1} + \frac{t_w}{k_w}\right\}^{-1}$$

$$T_{w,o} = T_{\sin k} + \frac{T_v - T_{\sin k}}{h_{o,e}}\left(\frac{1}{h_{o,e}} + \frac{1}{\bar{h}_{i,e}}\right)^{-1}$$

# Heat Transfer in the Condenser

The thickness of the condensed liquid film:

$$-\frac{\sigma\delta^3}{3\nu_l}\frac{d^3\delta}{dz^3}=\frac{k_l\,(T_{sat}-T_w)}{h_{fg}}\int_0^z\frac{1}{\delta}dz$$

B.C: $\left.\frac{d\delta}{dz}\right|_{z=0}=0$ $\quad\left.\frac{d^3\delta}{dz^3}\right|_{z=0}=0$

Assuming the thickness of liquid film:

$\left.\frac{d^2\delta}{dz^2}\right|_{z=l_{w0}}=\frac{1}{r_m}$ $\quad\left.\frac{d\delta}{dz}\right|_{z=lw0}=\tan\alpha$

$$\frac{\delta}{w}=C_0+C_1\frac{z}{w}+C_2\frac{z^2}{w^2}+C_3\frac{z^3}{w^3}+C_4\frac{z^4}{w^4}$$

$$\overline{h}_{c,f}=\frac{k_l}{\overline{\delta}}$$

$$\overline{h}_{c,f}=\frac{k_l}{wC_0}=\left[\frac{h_{fg}\rho_l\sigma k_l^{\,3}(l_{w0}/r_m-\tan\alpha)}{\mu_l l_{w0}^{\,3}(T_v-T_w)}\right]^{\frac{1}{4}}$$

# Heat Transfer in the Condenser

Film thickness of the liquid meniscus:

$$\delta = \delta\big|_{s=l_{w0}} + r_m \cos\alpha - \left[(r_m \cos\alpha)^2 - (z - l_{w0})^2 - 2r_m (z - l_{w0})\sin\alpha\right]^{\frac{1}{2}}$$

Heat transfer coefficient in meniscus:

$$\bar{h}_{c,men} = \int_{l_{w0}}^{2r_m \sin\beta_1 \sin\beta_2} \frac{k_l}{l_{ab}\left\{\delta\big|_{s=l_{w0}} + r_m \cos\alpha - \left[(r_m \cos\alpha)^2 - (z - l_{w0})^2 - 2r_m (z - l_{w0})\sin\alpha\right]^{0.5}\right\}} dz$$

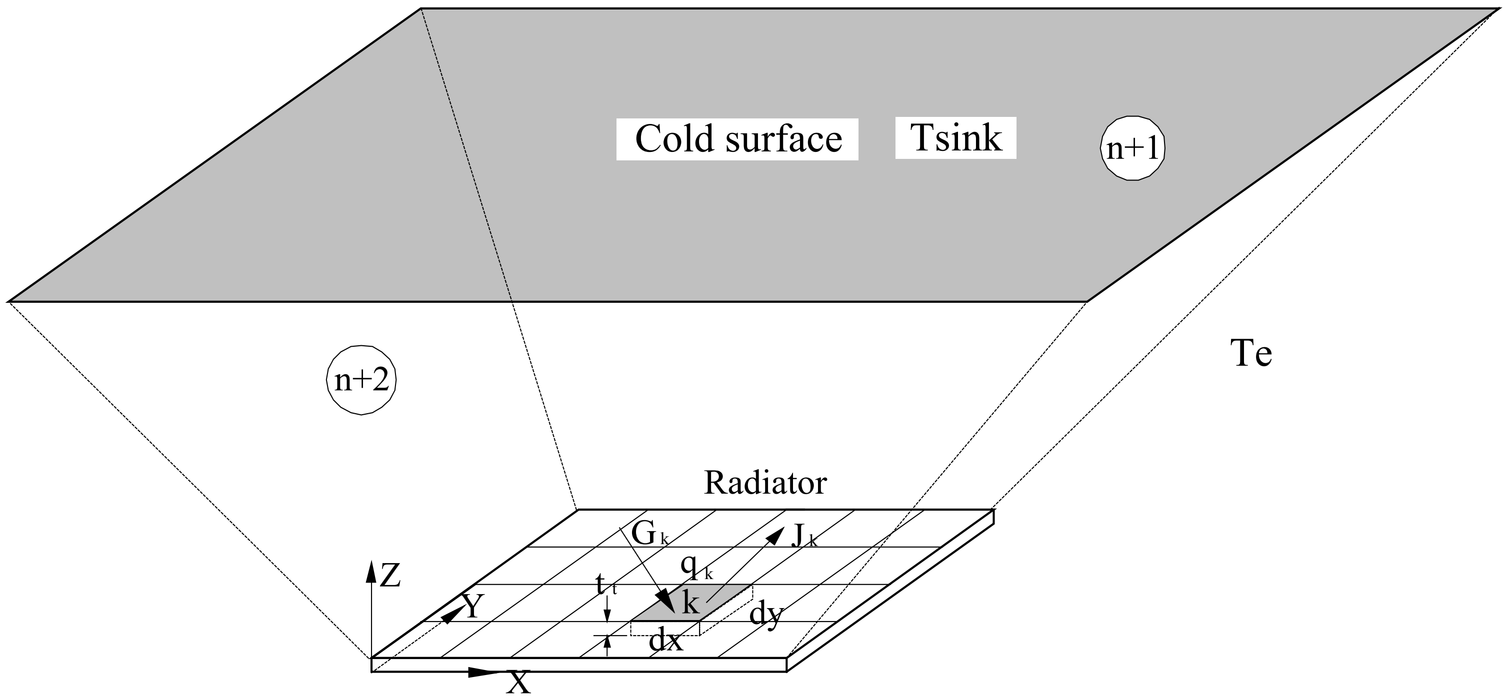
Heat transfer coefficient in the condenser

$$\bar{h}_c = \left\{\left[\frac{2l_{w0}}{w}\bar{h}_{c,f} + (1 - \frac{2l_{w0}}{w})\bar{h}_{c,men}\right]^{-1} + \frac{t_w}{k_w}\right\}^{-1}$$

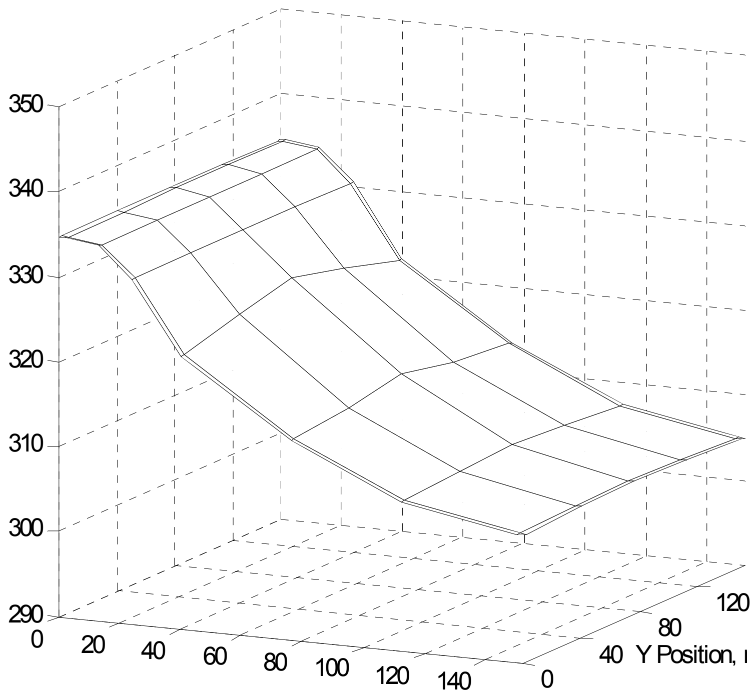
$$T_{w,o} = T_{c,o} + (T_v - T_{c,o})\frac{1}{h_{c,o}}\left(\frac{1}{h_{c,o}} + \frac{1}{\bar{h}_c}\right)^{-1}$$

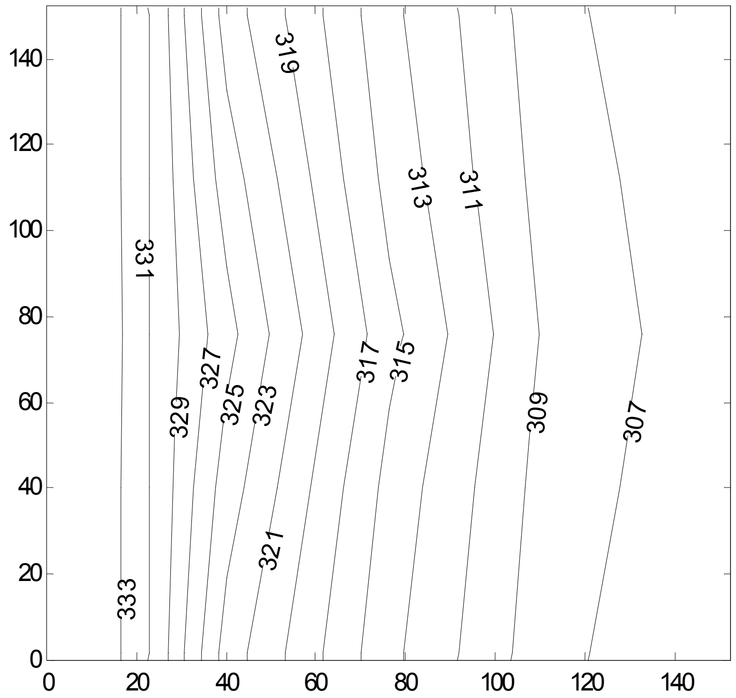
$$h_{c,o} = \varepsilon\sigma_0 (T_{w,o} + T_{\sin k})(T_{w,o}{}^2 + T_{\sin k}{}^2)$$

# Radiation Heat Transfer



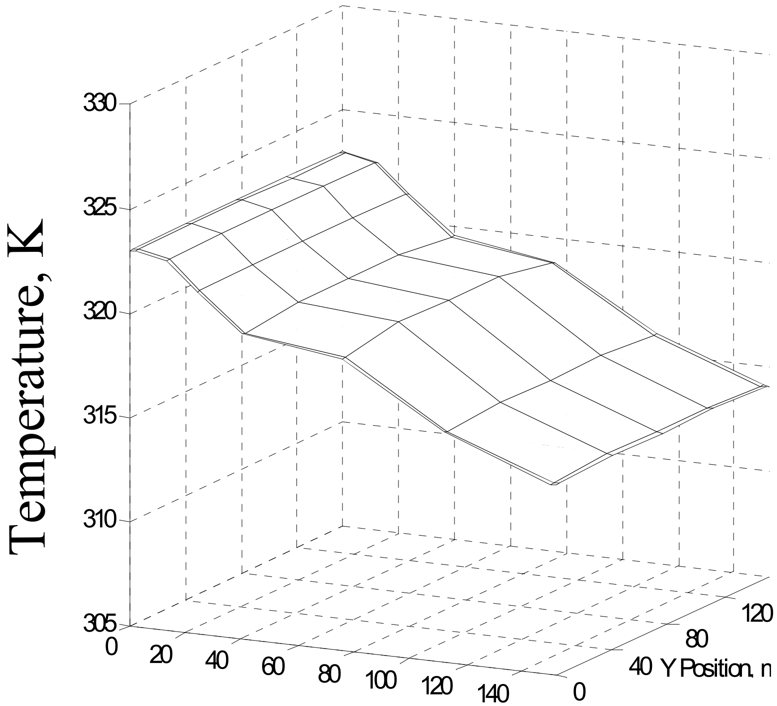
# Temperature Distributions on the Wire Bonded Micro Heat Pipe Radiator

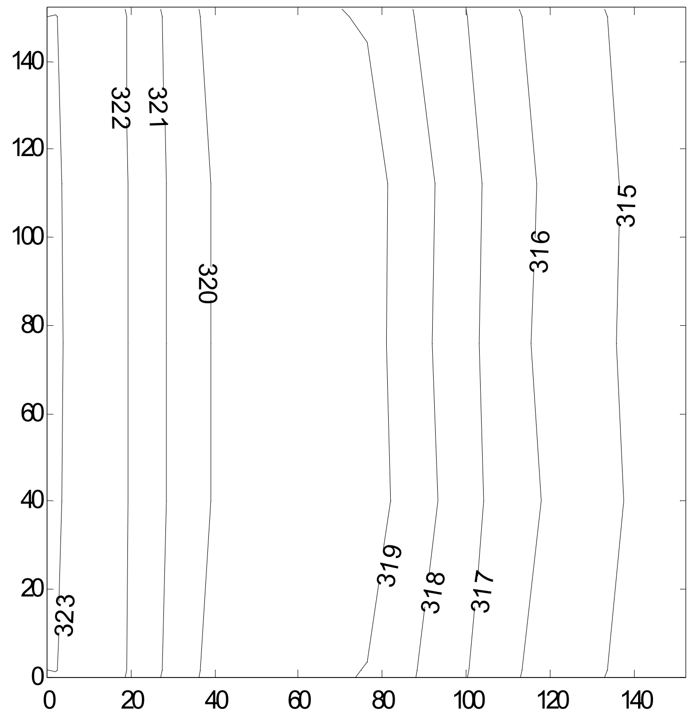



No fluid charge, dw=0.813 mm

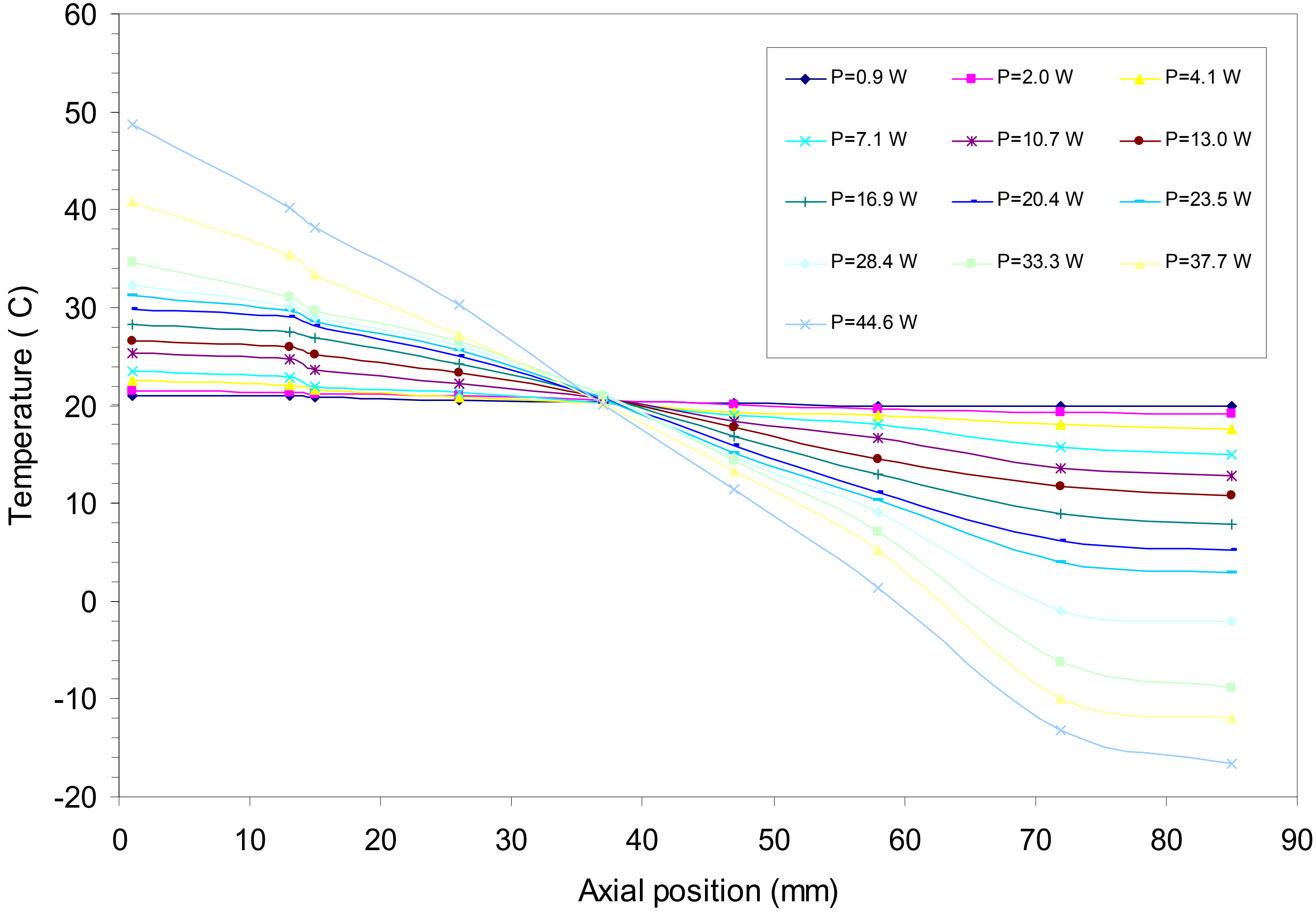
# Temperature Distributions on the Wire Bonded Micro Heat Pipe Radiator



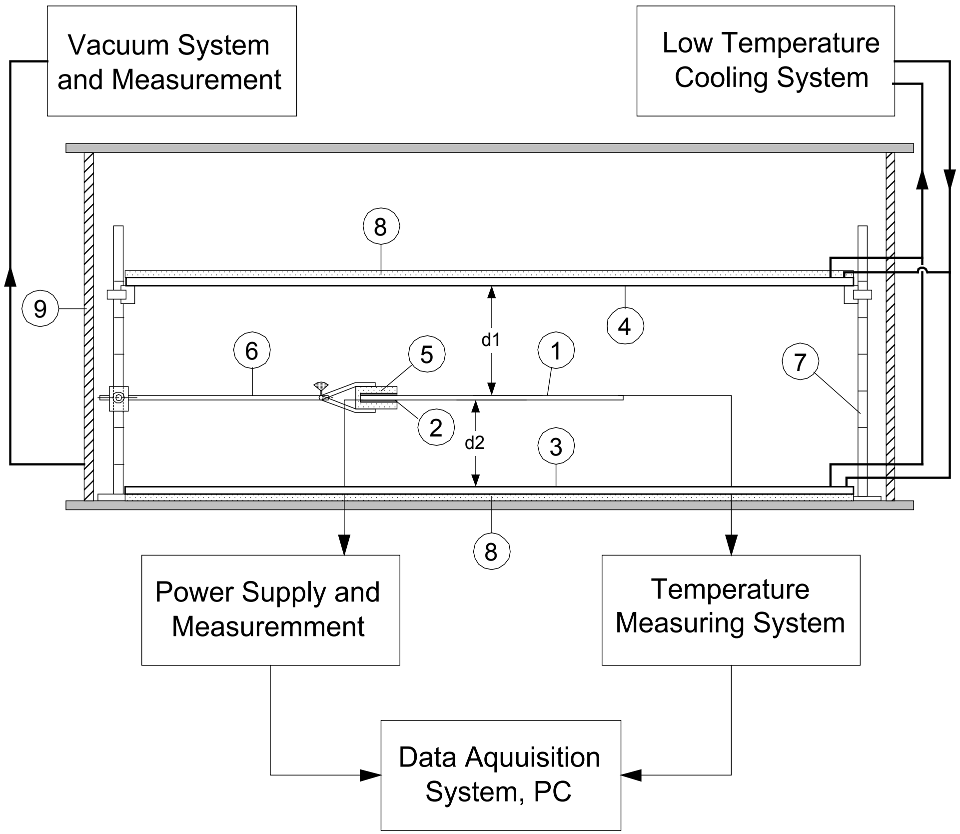




Charged with optimum charge, dw=0.813 mm

# Axial Temperature Distribution



# Test Facility for Radiation Environment



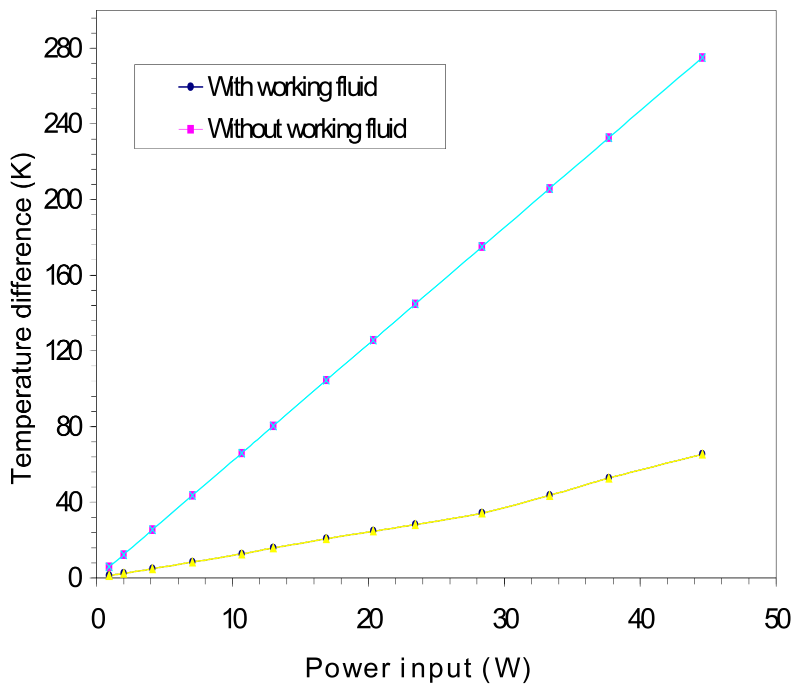

1. Micro heat pipe radiator
2. Electric heater
3. Bottom cold plate
4. Top cold plate
5. Electric heater insulation
6. Adjustable support level
7. Adjustable support feet
8. Insulation material
9. Vacuum chamber

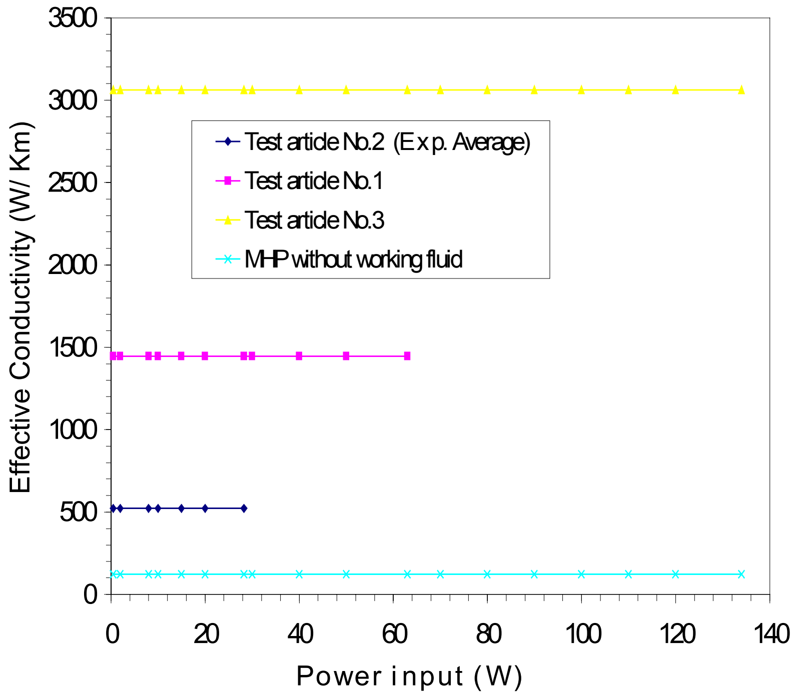
# Test Articles

| Prototype | No. 1 | No. 2 | No. 3 |
|---|---|---|---|
| Material | Aluminum | Aluminum | Aluminum |
| Working fluid | Acetone | Acetone | Acetone |
| Total Dimension (mm) | 152×152.4 | 152×152.4 | 152×152.4 |
| Thickness of sheet (mm) | 0.40 | 0.40 | 0.40 |
| Diameter of wire (mm) | 0.50 | 0.80 | 0.50 |
| Number of wires | 43 | 43 | 95 |

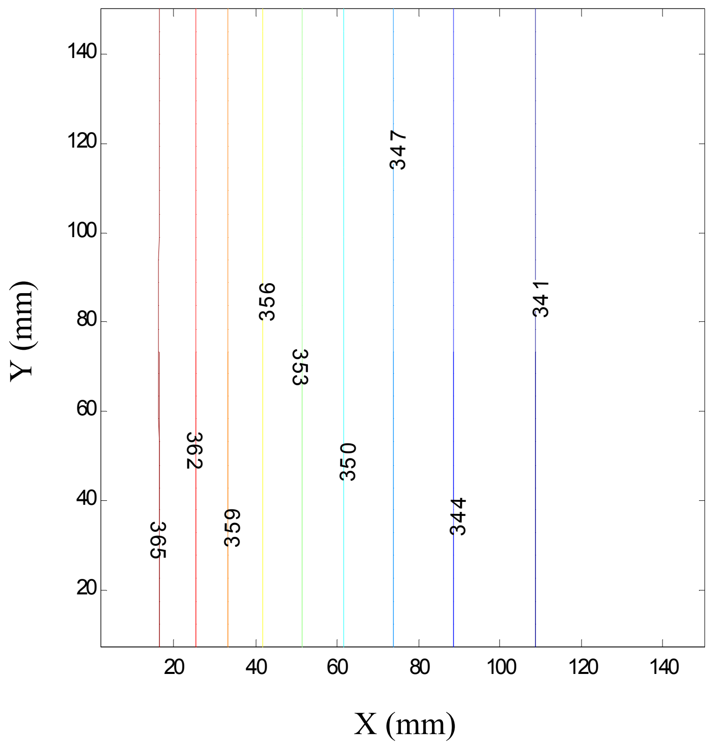
# Experimental Results

- **Effective Thermal Conductivity**

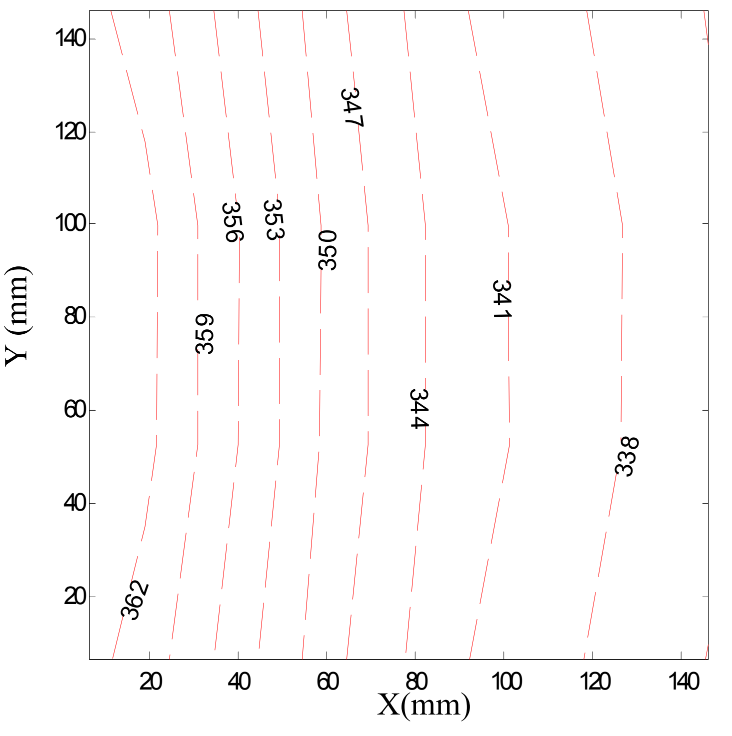


# Comparison of Experimental and Predicted Results

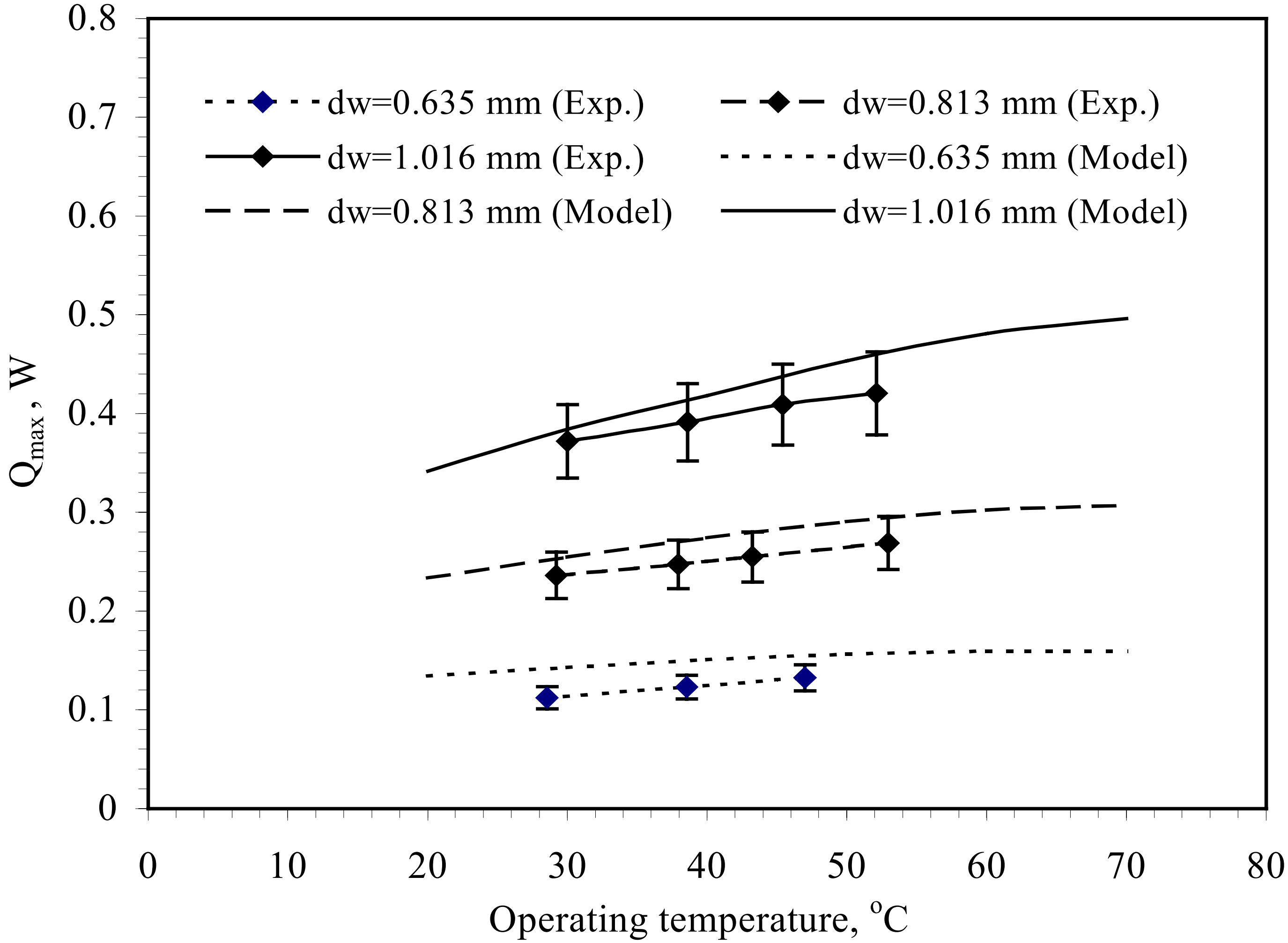


Modeled Temperature Distribution

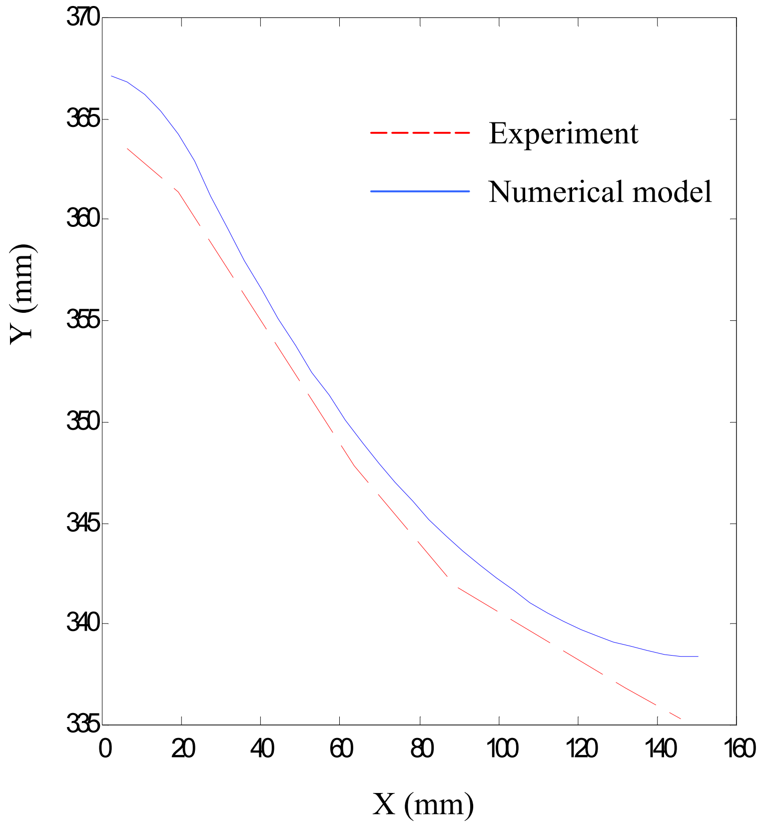


Measured Temperature Distribution

# Comparison of the Predicted Experimental Results

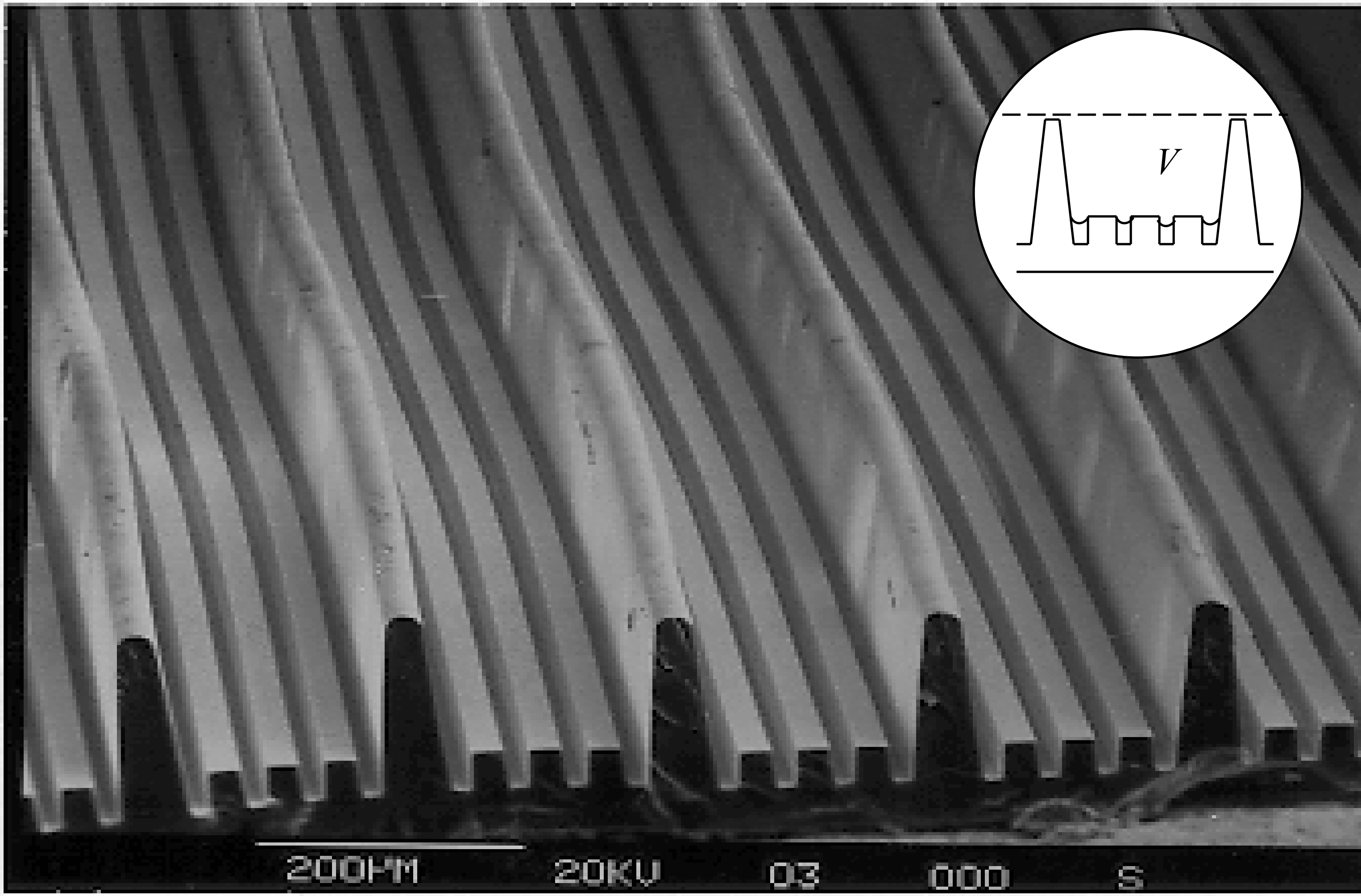


# Comparison of Experimental and Predicted Results

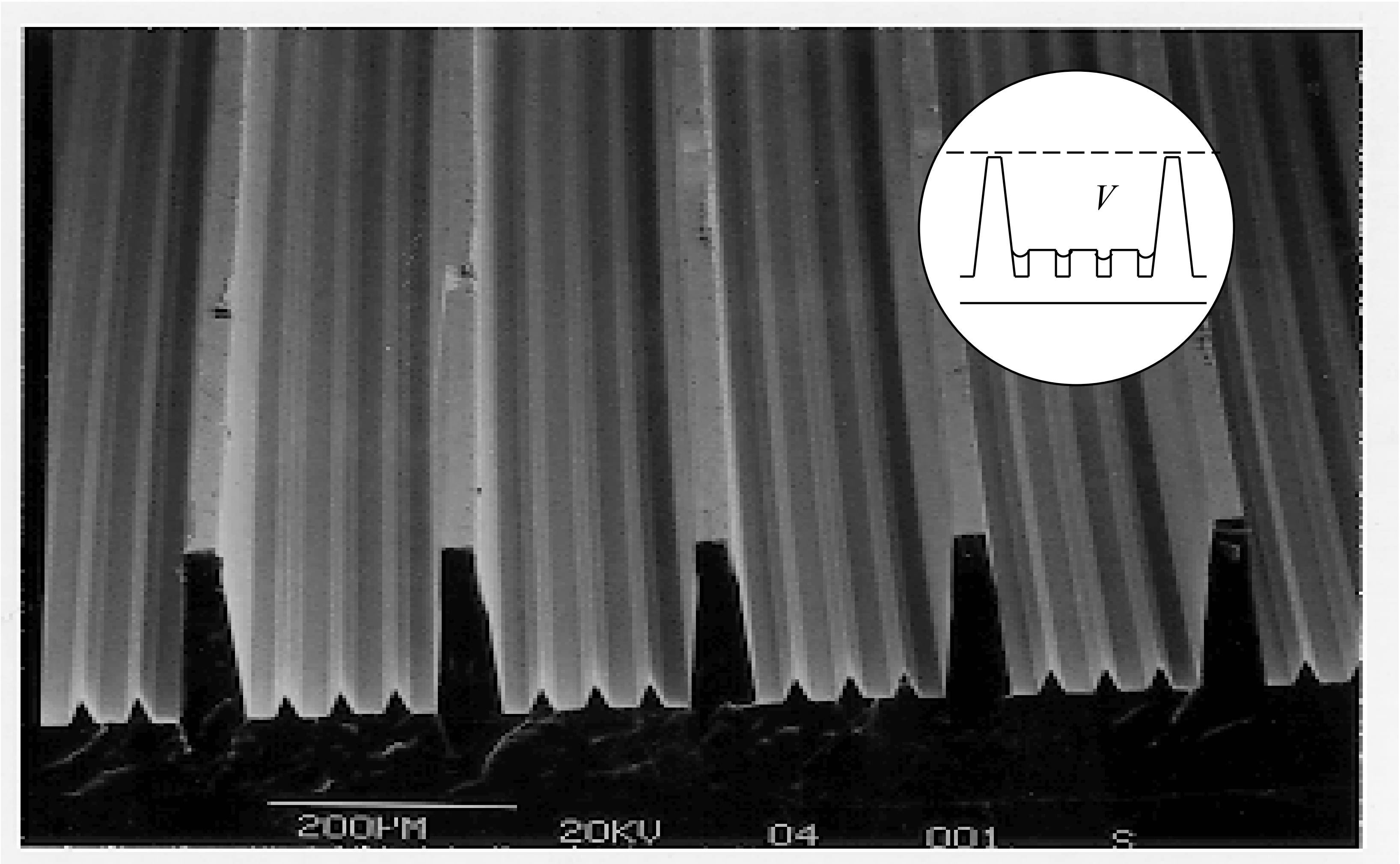



- Temperature distribution obtained from the experiment was slightly lower than from the model.
- Heat loss may result from conduction through the support and insulation and edge radiation
- Total difference is less than 6.8%

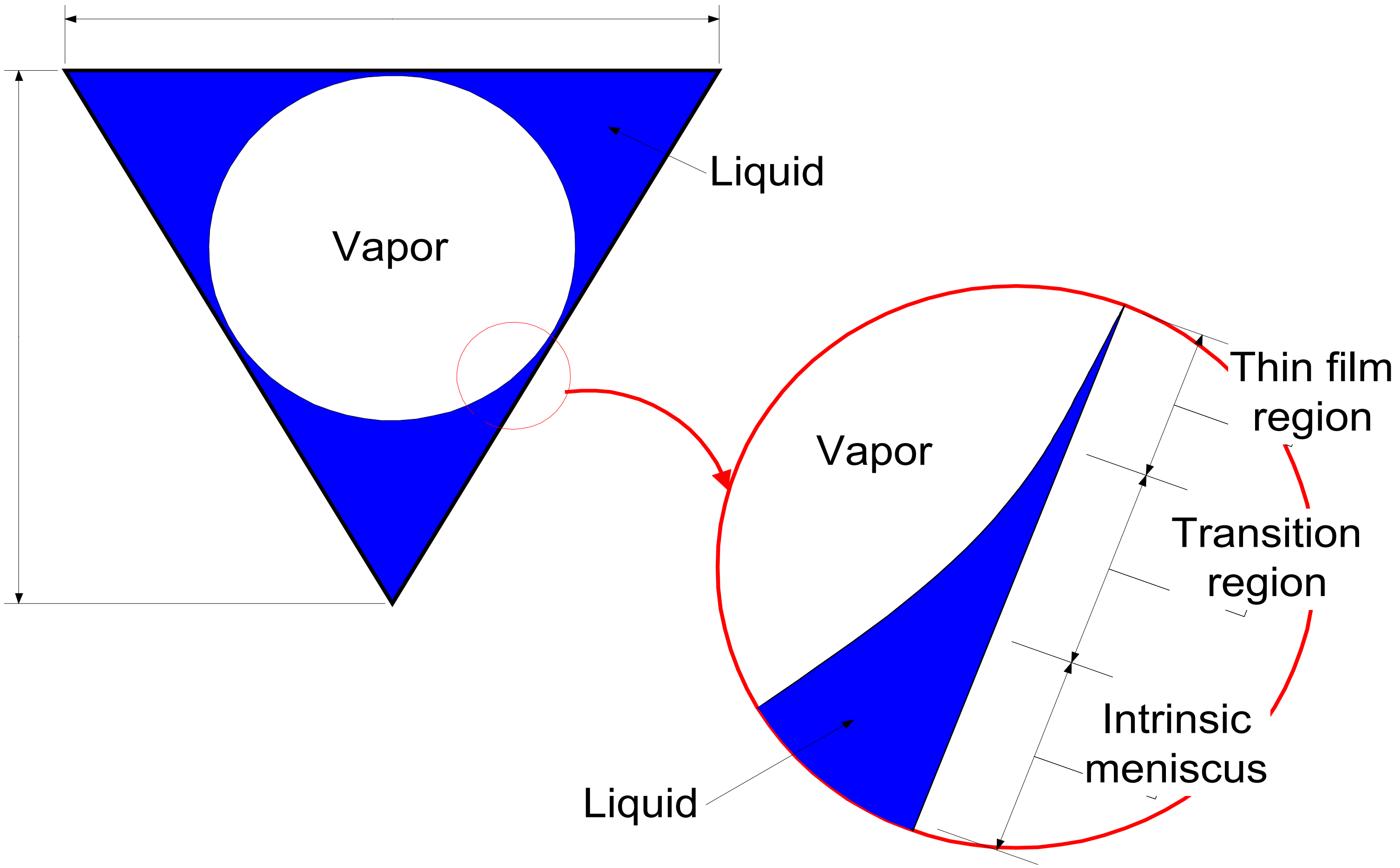
# Rectangular Polymer Heat Pipe



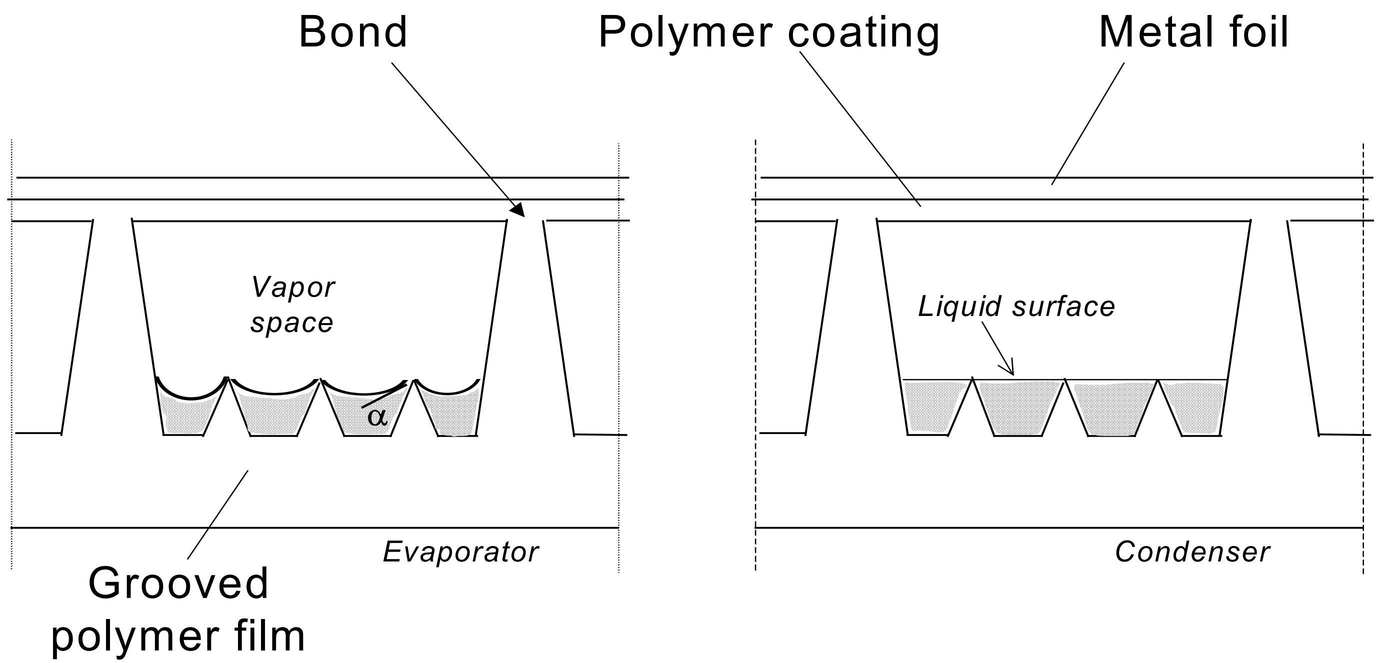
# Triangular Polymer Heat Pipe



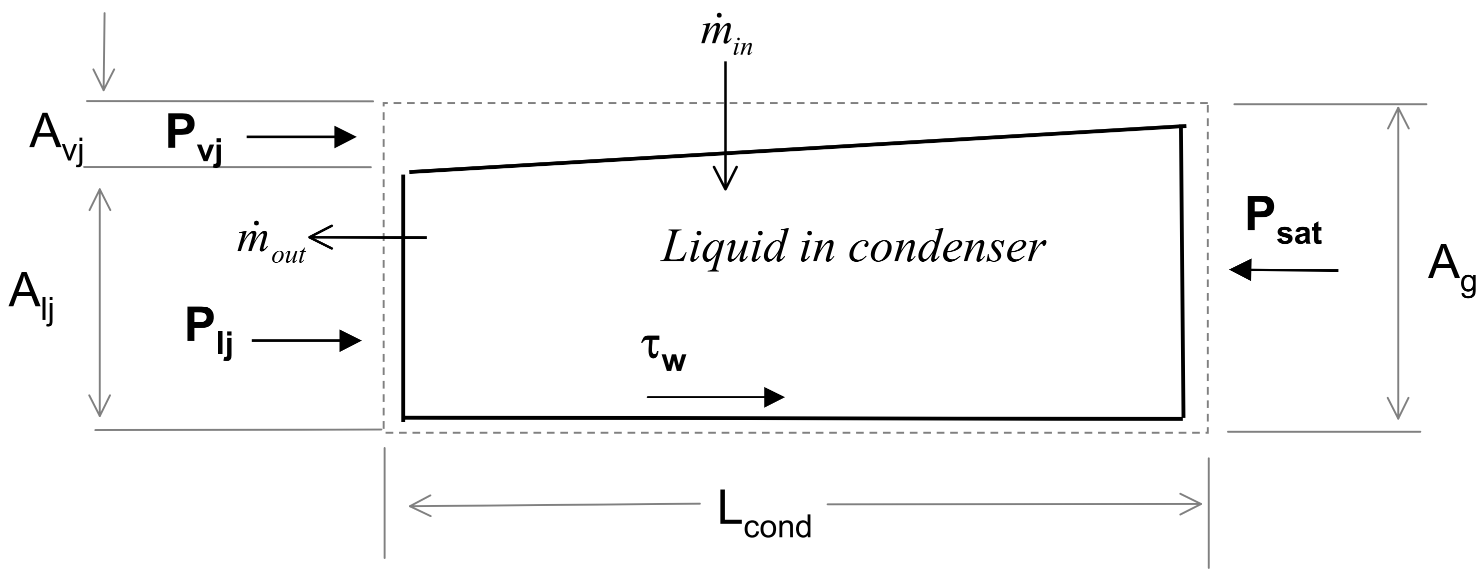
# Interfacial Region



# Polymer Micro Heat Pipe



# Momentum Balance




(Fig. 13)

# Numerical Model

The governing equation for two-dimensional plate conduction combined with a radiation boundary condition can be expressed as,

$$\frac{\partial}{\partial x}\left(ttk_{eff,x}\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(ttk_{eff,y}\frac{\partial T}{\partial y}\right)-q_k+q_0=0 \qquad (1)$$

if $q_k$ is the net radiation transfer through the control volume k, this equation can be expressed as,

$$\sum_{j=1}^{n+2}\left(\frac{\delta_{kj}}{\varepsilon_j}-F_{k-j}\frac{1-\varepsilon_j}{\varepsilon_j}\right)q_j=\sum_{j=1}^{n+2}(\delta_{kj}-F_{k-j})\sigma T_j^4 \qquad (2)$$

where $\delta_{kj}$ is the Kronecker delta defined as,

$$\delta_{kj}=\begin{cases}1 & when \quad k=j\\ 0 & when \quad k\neq j\end{cases}$$

# Numerical Model

For the case of constant thermal effective conductivity for the micro heat pipe array, Eq. (1) becomes,

$$K_{eff,x}\frac{\partial^2 T}{\partial x^2}+K_{eff,y}\frac{\partial^2 T}{\partial y^2}-q_k+q_0=0 \qquad (3)$$

where $K_{eff,x}$= t $k_{eff,x}$, and $K_{eff,y}$= t $k_{eff,y}$
The discretization equation is,

$$a_1 T_{i-1,j}{}^{n} - a_2 T_{i,j}{}^{n} + a_1 T_{i+1,j}{}^{n} = c_1 - c_2 (T_{i,j}{}^{n-1} + T_{i,j-1}{}^{n-1}) \qquad (4)$$

where

$$a_1=\frac{K_{eff,x}}{\Delta x^2}, \qquad a_2=2\left(\frac{K_{eff,x}}{\Delta x^2}+\frac{K_{eff,y}}{\Delta y^2}\right)$$

$$c_1=(q_k-q_0), \qquad c_2=\frac{K_{eff,y}}{\Delta y^2}$$

# Numerical Model

Adiabatic boundary condition on the edges are assumed , i.e.,

$$\frac{\partial T}{\partial x} = 0 \quad \begin{cases} at\ x = 0, & 0 \le y \le 152.4\,mm \\ at\ x = 152\,mm, & 0 \le y \le 152.4\,mm \end{cases}$$

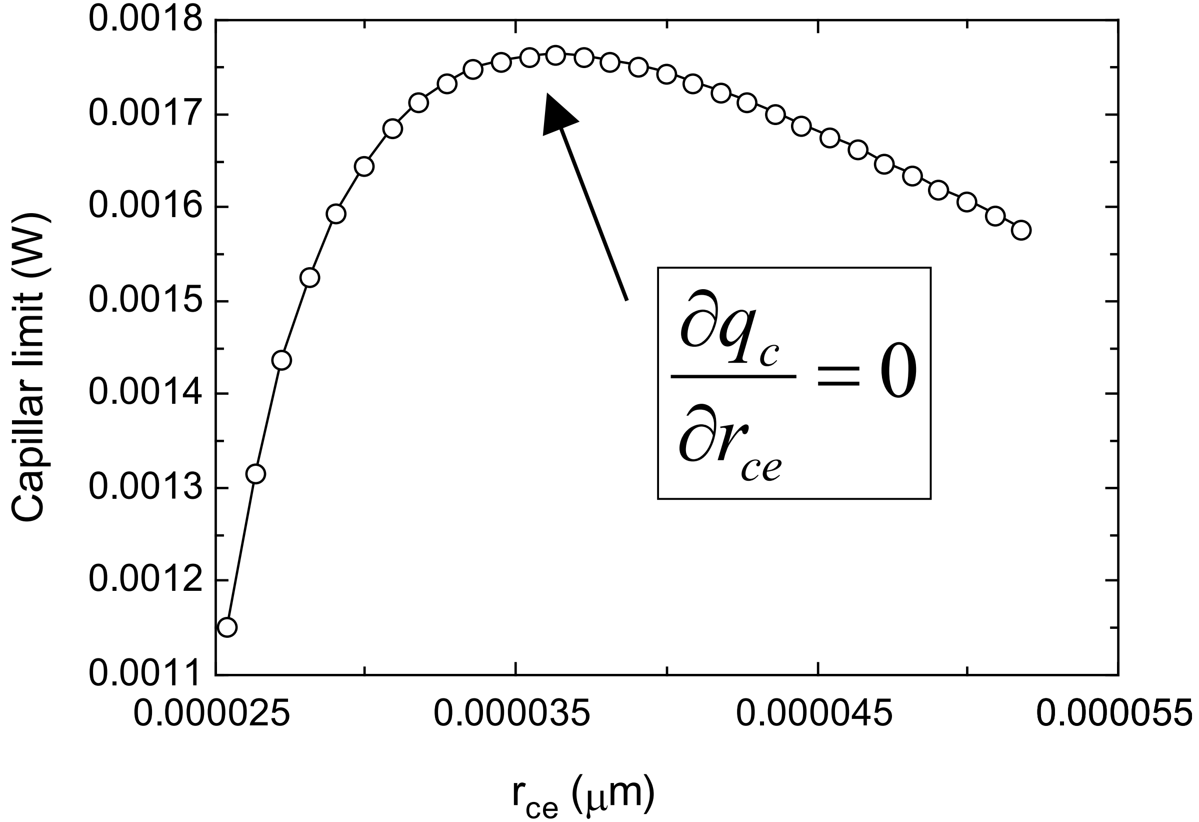
$$\frac{\partial T}{\partial y} = 0 \quad \begin{cases} at\ y = 0, & 0 \le x \le 152\,mm \\ at\ y = 152.4\,mm, & 0 \le x \le 152\,mm \end{cases}$$

and

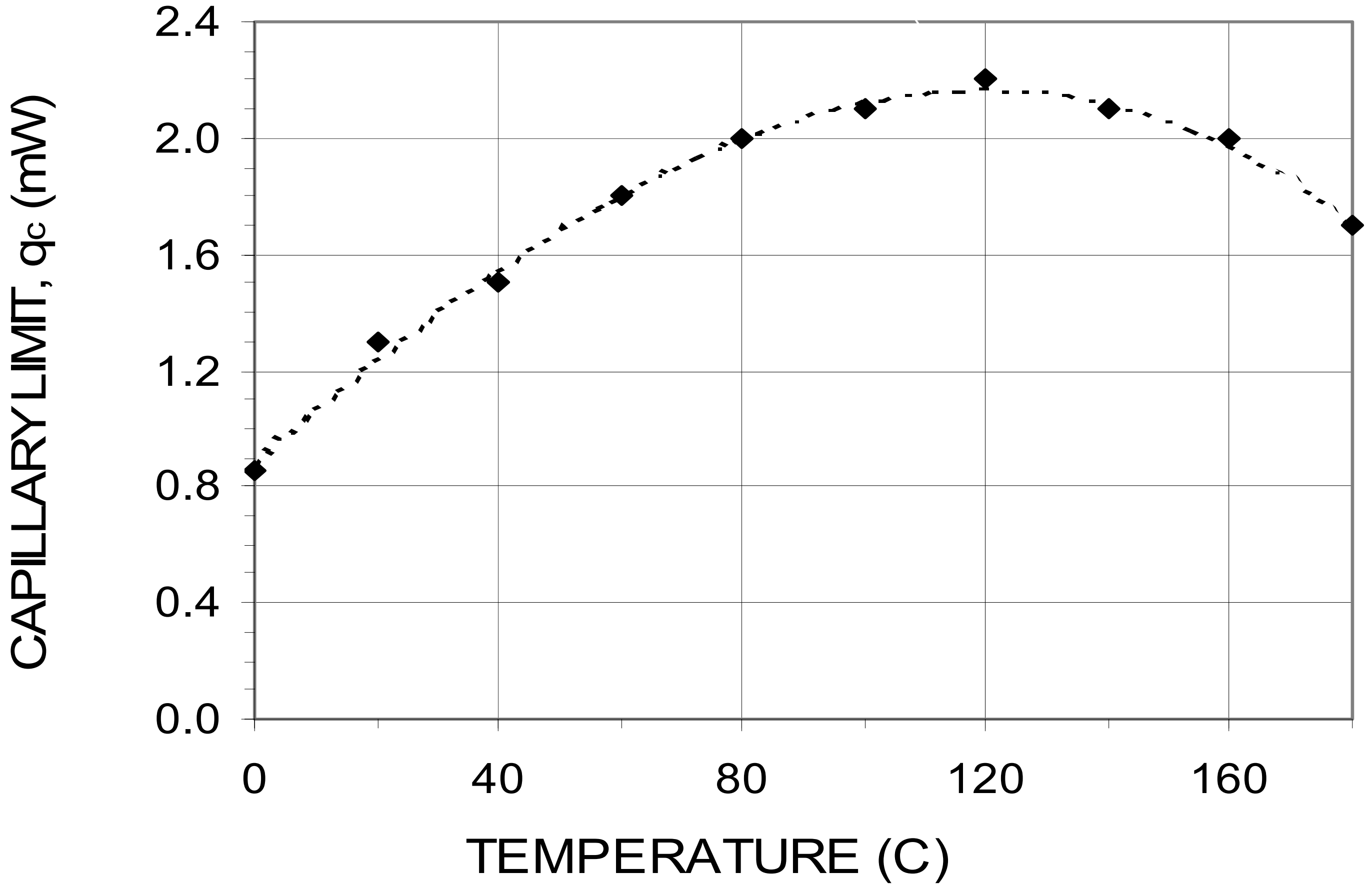
$q_0 = q_{input}$, 0 x ≤25.4 mm, 0 ≤ y ≤ 152.4 mm

$q_0 = 0$, x > 25.4 mm, 0 ≤ y ≤ 152.4 mm

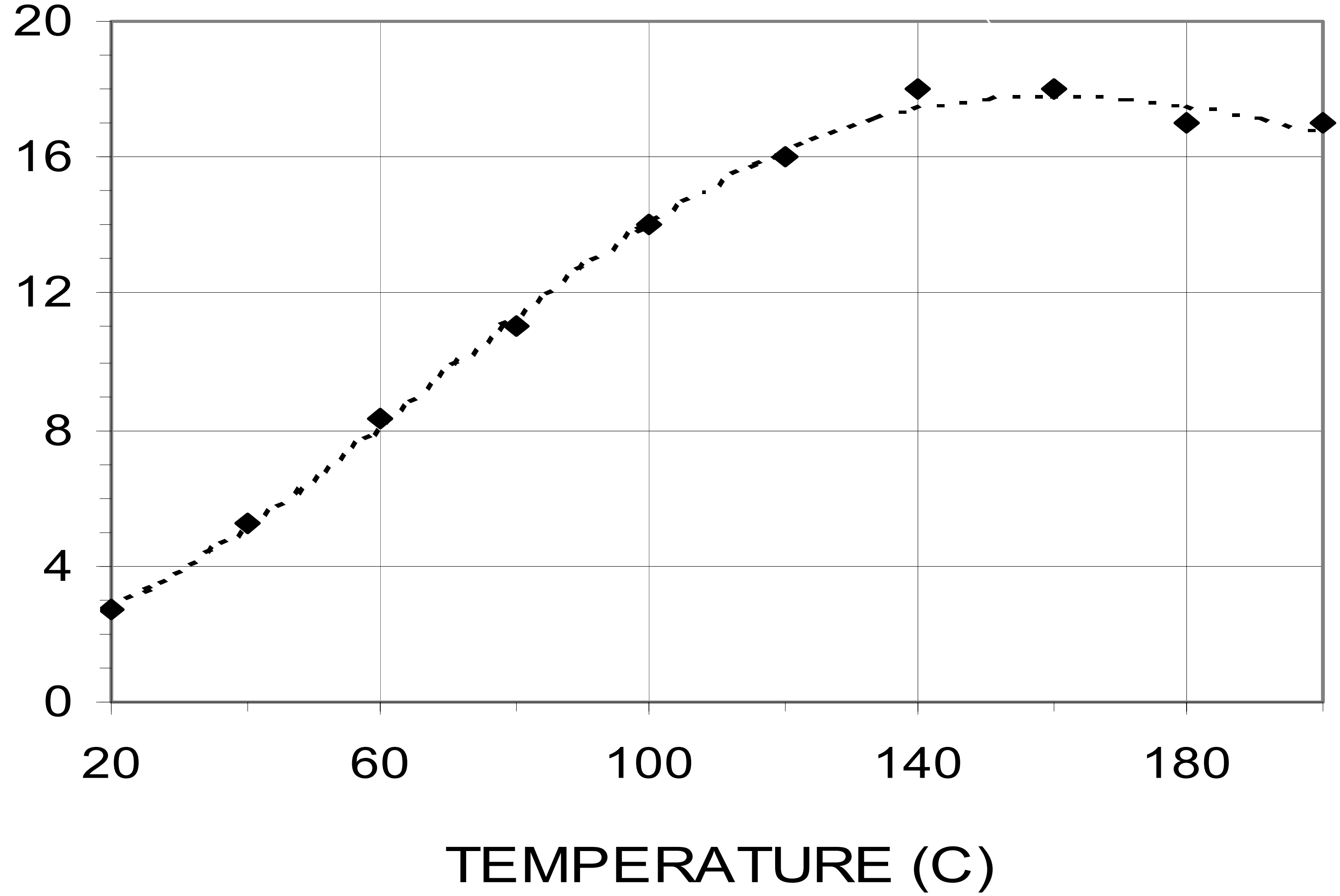
# Optimum Capillary Radius



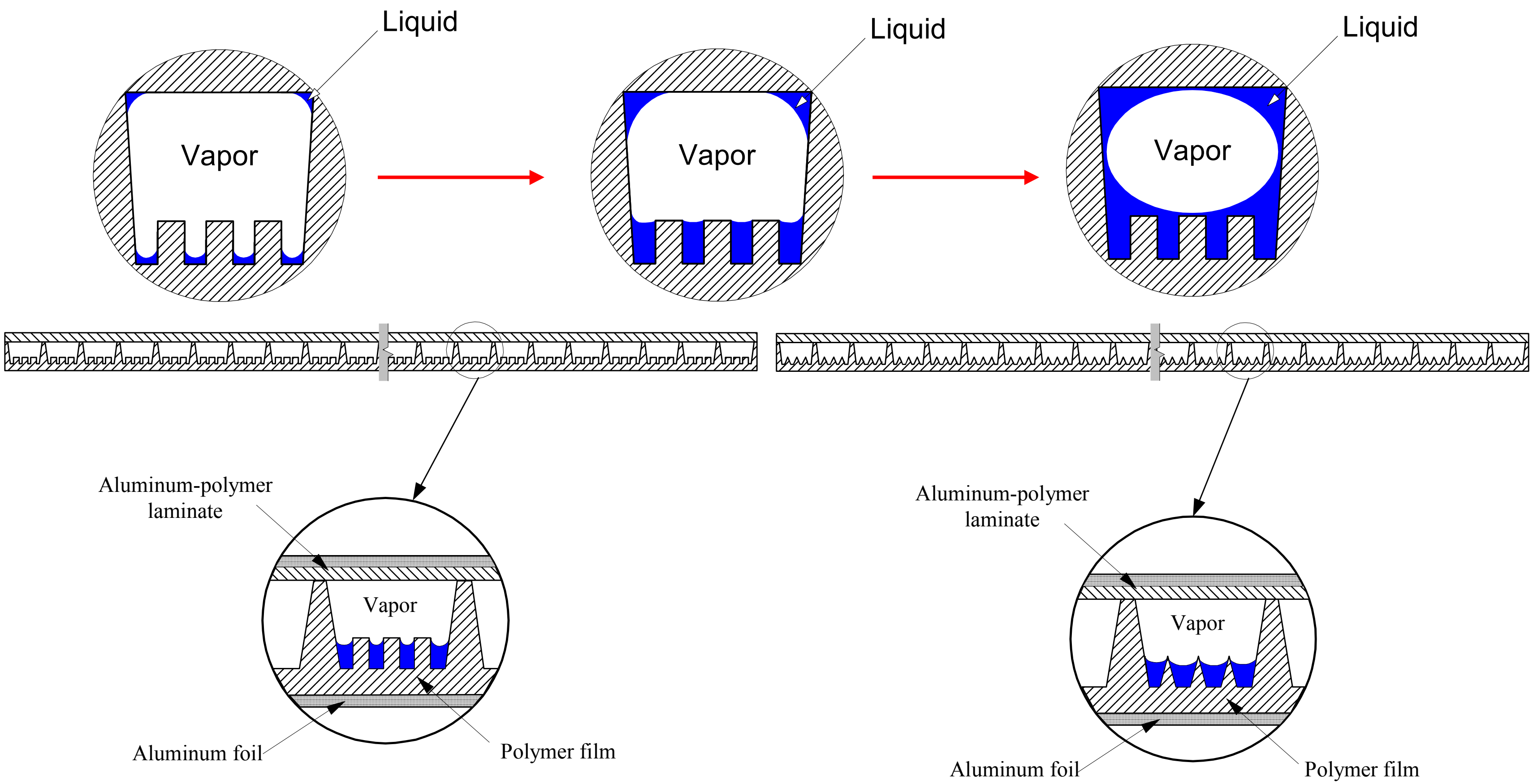
# Capillary Limit - Methanol



# Capillary Limit Water



# Stable Liquid Configurations



# Summary and Conclusions

- Two new micro heat pipe concepts have been developed
- Wire Bonded heat pipe arrays with an effective conductivity of 30 times that of solid aluminum have been developed and tested.
- Flexible polymer heat pipes have been fabricated and modeled.
- These polymer heat pipes offer a greater degree of flexibility and a potentially higher effective thermal conductivity than any previously developed.
- Applications of the these two concepts have a wide range of applications that extends well beyond spacecraft radiators.